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Yang, Yi; Heijungs, Reinout

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COMMENTARY AND DISCUSSION ARTICLE

Moving from completing system boundaries to more realistic modeling of the economy in life cycle assessment

Yi Yang[1] · Reinout Heijungs[2,3]

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Abstract

Purpose Existing process-based life cycle assessment (LCA) models can be supplemented by input-output (IO) models to correct for the so-called truncation error resulting from an "incomplete" system boundary. The resulting hybrid LCA is not necessarily but probably a closer approximation to an ideally complete process model with a global all-inclusive system boundary. Here, we discuss whether such a complete process model is a goal worth pursuing and whether system boundary is the main limitation of process-based LCA.

Methods We argue that the results of the ideally complete process model, with every single economic activity on earth embodied within, have little to limited implications and relevance for the decisions which LCA seeks to support and which involve changes aimed at reducing environmental impacts through altering product systems or promoting alternatives. The main limitations of process-based LCA, as a supply chain based linear model, lie not in the "incomplete" system boundary but in the narrow focus on supply chain and the unrealistic assumptions, such as omission of price effects and constraints. These assumptions reflect poorly how the economy works. Hybrid LCA, through adding IO models, which are also supply chain and linearity based, doubles down on both the narrow focus on supply chain and the unrealistic assumptions, and thus is a step forward but in the wrong direction.

Results and discussion Reflecting on advances in corn ethanol research, we show that pursuing a more complete system boundary by, for instance, covering Chinese stuffed animal production does not make the LCA results more accurate or relevant for determining if corn ethanol in the US should be promoted. Not only is the theoretical argument for including Chinese stuffed animal industry tenuous, but there is no evidence it has been affected by US corn ethanol expansion. And by worrying about processes far away up the supply chain could distract us from focusing on the actual market mechanisms, such as indirect land use change, that are more likely to occur and are essential to predicting whether promoting corn ethanol would reduce total carbon emissions.

Conclusions We suggest future studies shifting focus from "completing" system boundary within the conventional supply chain and linear framework towards more realistic modeling of our complicated human-environment system. Instead of trying to always include everything, we argue for a flexible and market-based system boundary tailored to the decision in question, particularly considering the scale of potential changes it may cause and how it may affect the economy. A change at larger scales is likely to have a broader impact, thus justifying the definition of a broader system boundary. But to cover a broad system boundary for a small change will likely result in overestimates. More is not necessarily better.

Keywords Hybrid life cycle assessment · Consequential · System boundary · Marginal changes

Responsible editor: Mary Ann Curran

✉ Yi Yang
yang1385@umn.edu

1 Department of Ecology, Evolution, and Behavior, University of Minnesota, St. Paul, USA

2 Department of Econometrics and Operations Research, Vrije Universiteit Amsterdam, Amsterdam, Netherlands

3 Department of Industrial Ecology, Institute of Environmental Sciences, Leiden University, Leiden, Netherlands

1 Introduction

In an earlier article, we demonstrated that hybrid life cycle assessment (LCA) *does not necessarily yield more accurate results* than process-based LCA (Yang et al. 2017). The central argument of ours was that the so-called truncation error of process-based LCA could be outweighed by the aggregation error of the input-output (IO) model. Pomponi and Lenzen (2018) contended that that hybrid LCA *will likely yield more accurate results*.

The conclusions of the two papers are not in conflict: "A is likely more accurate than B" is a subset of "A is not necessarily more accurate than B." We indeed agree that hybrid LCA probably yields more accurate results than process-based LCA, in the sense that *hybrid LCA is*, *in most realistic cases, probably a closer approximation to process-based LCA with a complete global system boundary, compared with one without such a system boundary*. But in the original paper (Yang et al. 2017), we emphasized the "not necessarily more accurate" part of the implication mainly because hybrid LCA had been overwhelmingly claimed by its practitioners as a more advanced or more accurate model than process-based LCA. Moreover, such claims were never presented as hypotheses but rather as self-evident: hybrid LCA being more complete (which we did not deny) would obviously be more accurate (which we challenged).

Having said that, here we raise a more fundamental question: *is a process-based LCA model with a complete global system boundary covering every single economic activity in every country a goal worth pursuing?* This question stems from a point made by Pomponi and Lenzen (2018) that we believe is a major misunderstanding of the use and purpose of the IO model that must be subject to analysis and debate. We are referring to their statement on page 210 that "Forecasting future changes in total output as a result of changes in final demand is not an exercise that is intended to be carried out using input-output tables."

As is to be demonstrated, a process model with a complete global system boundary is not a goal worth pursuing for most policy-relevant studies. It may be interesting mathematically and may have some policy relevance in the context of finding hotspots (e.g., agriculture accounts for 25% of total greenhouse gas emissions). But ultimately, it has little to limited implications and relevance for our decision making aimed at changing and improving the current system. The main limitations of process-based LCA lie not in the "incomplete" system boundary but in its unrealistic assumptions such as linearity and omission of price effects and various constraints. Adding IO to the process model with further linear sophistication doubles down on the unrealism of these assumptions and thus is a step forward in the wrong direction. In a sense, it resembles the medieval idea that adding epicycles and deferents to the Ptolemaic cosmological model would repair the defects of the model. We suggest future studies (1) shifting focus from "completing" system boundary towards more realistic modeling of our complicated human-environment system and (2) applying a flexible system boundary tailored to the decision in question, especially considering the scale of potential changes it may cause and how it may affect the economy.

2 Yes, hybrid LCA is probably a closer approximation of process-based LCA with a complete global system boundary

Although we agree with the conclusion by Pomponi and Lenzen (2018), their reasoning is not accurate. They pointed out that in our original example, processes/sectors were loosely interconnected (with a low dominant eigenvalue), resulting in a relatively low truncation error for process-based LCA. Real economies, they suggest, have higher levels of interconnectedness, hence higher eigenvalues and likely higher truncation errors. This may be rightly so, but it is only one side of the equation. The other is the aggregation error of IO models. Using their example that has a large truncation error, we can easily modify and make the aggregation error greater so that the incomplete process-based LCA would again yield more accurate results.

The reason a hybrid LCA is probably a closer approximation is a matter of probability. Because we do not have a perfect and complete process-based LCA model that connects everything in the world, we do not know the magnitude of either the truncation error or the aggregation error. Theoretically, however, in order for the aggregation error to outweigh the truncation error, the estimate for an aggregate sector given by an IO model must be much larger than the estimate for the missing input—for which the IO sector substitutes—given by a complete process-based model. If the former is somewhat larger, equal, or smaller, hybrid LCA would yield results closer to the "true" values as given by the complete process model. Let us consider our original example (Yang et al. 2017). The estimate for agriculture given by the IO model must be twice the estimate for corn given by the complete process model (4.8 versus 2.4 kg/kg) in order for the incomplete process-based LCA to be a more accurate approximation of the complete process LCA than the hybrid LCA. Any value below 4.8 kg/kg would render otherwise.

How hybrid LCA works boils down to the extent to which the missing inputs in a process model can be approximated by the IO model introduced relative to their "true" values given by a complete process model, which is unknown. The IO model may yield underestimates, approximates, slight overestimates, or significant overestimates, depending on the heterogeneity of the subsectors aggregated. Only when significant overestimates were given would the aggregation error outweigh the truncation error and hybrid LCA underperform process-based LCA. Statistically speaking, however, significant overestimates are not as probable as the other three outcomes. This is especially true when there are a large number of missing inputs in a process model. That said, it is still possible that process LCA could outperform hybrid LCA when the truncation error is low and the aggregation error relatively high.

3 What is LCA about?

Being probably a closer approximation to a "complete" process LCA model, hybrid LCA seems a step forward in methodology development. But a more fundamental question arises, is such a complete model that connects every economic activity in the world worth pursuing? How to address this question is the focus of the rest of the paper, and we begin by asking an even more fundamental question, what is LCA about?

Which brings us to the statement by Pomponi and Lenzenis (2018) that "Forecasting future changes in total output as a result of changes in final demand is not an exercise that is intended to be carried out using input-output tables" (page 210). This statement, we believe, reflects a major misunderstanding of the use and purpose of the IO model. One need to look no further than the classic IO textbook by Miller and Blair (2009) to see that estimating future changes in total output as a result of changes in final demand is precisely the primary goal and use of the IO model. A few quotations suffice to make our point (italics have been added for emphasis):

- "We can now ask the question: If final demand for agriculture output were to *increase* to \$600 next year and that for manufactures were to *decrease* to \$1500—for example, because of *changes* in government spending, consumers' tastes, and so on—how much total output from the two sectors would be necessary in order to meet this *new* demand?" (Chapter 2: Foundations of Input-Output Analysis, page 22)
- "For example, assume that there is an *increase* of ¥100,000 in export demand for manufactured goods from the North." (Chapter 3: Many-Region Models: The Interregional Approach, page 97)
- "One of the major uses of the information in an input-output model is to assess the effect on an economy of *changes* in elements that are exogenous to the model of that economy." (Chapter 6: Multipliers in the Input-Output Model, page 243)
- "A very common public policy analysis problem is to analyze the implications of a *new* spending program" (Chapter 10: Environmental Input-Output Analysis, page 447)

Further, we can look in the broad economics literature regarding the goal and use of IO model. For example, Thirlwall (1983) described:

- "Input-output analysis is a particular *planning and forecasting* technique with a wide variety of applications."

Walter Isard, who developed the interregional IO model, stated the following, when comparing his regional IO approach with that of Leontief's (Isard 1951):

- "The Leontief balanced regional model is particularly useful for determining regional *implications of national projections*."

Ten Raa (2006) wrote:

- "[Leontief's] solution was to assume fixed and given capital coefficients. *Changes* in output, in his approach, imply rigidly predetermined *changes* in the quantities of capital required."

In addition, the IO model was often juxtaposed with the computable general equilibrium (CGE) model (Rose 1995; West 1995). CGE has been a standard tool used in economics to evaluate system-wide effects of changes, commonly due to policy interventions from fiscal reform, development planning, trade tariff, to environmental regulations (Dixon and Jorgenson 2012). In the eyes of economists, the IO model is also a kind of applied equilibrium model used to determine impacts of changes (Dervis and Dervis 1982).

When coupled with environmental data, the IO-based LCA model, or process-based and hybrid LCA, serves the same primary purpose of impact analysis of changes resulting from our decisions. By doing LCA, our goal is to improve the system under study, which by definition involves changes (Weidema 2003). This is what LCA is about: study of changes. Every application of LCA, as listed in ISO (2006) from product development and improvement, strategical planning, to public policy making, and marketing, is concerned with changes. In some cases, the goal of studying changes is clear and explicit, as in biofuel LCA where the question is whether we could *reduce* GHG emissions if we were to *increase* production of biofuels (Farrell et al. 2006). Based on LCAs studies showing biofuels have lower life cycle GHG emissions than fossil fuels, they have been promoted in many countries by public policies, such as the Renewable Fuel Standard in the USA and the Renewable Energy Directive in the EU.

In other cases, the goal of studying changes may not be as explicitly stated but is nevertheless embedded in the recommendations or implications. It is common that a study defines its goal as, and devotes the majority of its manuscript to, comparing the life cycle emissions of products providing the same function and service. But then based on the comparative results, the study concludes or makes recommendations that *switching* from A to B, which implies *increasing* production of A and *decreasing* production of B, would reduce emissions. This is reflected, for example, in LCA studies of electric cars vs conventional cars, organic farming vs industry farming, and LED bulbs vs incandescent bulbs.

In yet other cases, an LCA may simply aim to quantify the life cycle environmental impacts of a certain product, such as chicken meat and polyvinyl chloride (PVC). Despite such apparently non-change oriented studies, the results often end up in comparative studies to indicate environmental impacts of changes, as done in Tilman and Clark (2014), who collected numerous food LCAs to examine how dietary *change* could impact our health and the environment. Or the results of such studies could be simply used to suggest how we can reduce emissions by consuming *less* plastics.

A seeming exception to this rule is hotspot or baseline analysis; for instance, LCA studies that conclude that 25% of the impacts of a building are due to its construction or IO studies that conclude that food products make up 30% of a household's impacts. In the end, however, such analyses are used for implementing changes as well. For example, the finding that nitrogen fertilizer is a major contributor in the life cycle of biofuels aims in part to show that this is an improvement opportunity we should focus on and reducing nitrogen use would lead to environmental benefits. Thus, the ultimate goal of LCA will ultimately and invariably always be about changes.

4 An expansive system boundary is a result of the unrealistic assumptions of linear models

Now that we are clear about the goal of LCA (and IO analysis), we can continue to evaluate our question if a complete process-based LCA model that connects every economic activity in the world is worth pursuing. The argument of hybrid LCA is that because every economic activity is in theory connected with every other one, a process-based LCA model with an incomplete system boundary would leave out potentially large amounts of emissions and resource use unaccounted, hence the truncation error. But is this the major problem of process-based LCA? No, we argue.

The major problem with process-based LCA (or IO-based and hybrid LCA), when it is used to estimate changes, lies in the linear assumptions, which have been explicated previously (Rose 1995; West 1995; Lundie et al. 2007; Ferng 2009; Yang 2016, 2017; Yang and Heijungs 2018). Briefly, these linear models predict that, whatever is changed in final demand ($\Delta\mathbf{f}$) and of whatever magnitude, it would always affect every process/sector in the system, causing them to expand or shrink in proportion to the change, dictated by fixed technical coefficients, with no economies or diseconomies of scale, nor supply-side constraints, nor any price effects (Eq. 1). The reason every process/sector in A could be affected—hence the global all-inclusive system boundary argued for by hybrid LCA theorists—is partly reflected by the fact that few elements of matrix $\mathbf{A}^{-1}$ will be zero. For instance, while for ecoinvent v2.2 only 0.3% of matrix $\mathbf{A}$ is zero, this number explodes to more than 50% for matrix $\mathbf{A}^{-1}$ (Heijungs 2012). This means that the life cycle inventory of an average product would involve the life cycle inventory of more than 50% of all products and that a change to any process would affect more than 50% of all processes.

$$\Delta\mathbf{E} = \mathbf{B}\mathbf{A}^{-1}\Delta\mathbf{f} \tag{1}$$

Just think of your decision at lunch today to have an extra yoghurt. The linear models would predict that the extra amount of yoghurt would lead to an increased production of yoghurt, an increased production of fodder, of tractors, etc. The "domino" effect would go on until every process or sector in the economy has expanded a little bit. If it is a global multiregional model that covers every economic sector in every country, the effect is assumed to extend to them all. In other words, the more processes or sectors we put in $\mathbf{A}$, the larger the results ($\Delta\mathbf{E}$). But given the restrictiveness of the assumptions to begin with, this "domino" effect gets less and less likely for processes or sectors further up the supply chain. What is, for example, the likelihood that a once-only tiny-scale indulgence in yoghurt in Netherlands would lead souvenirs stores in Yunan China that make and sell indigenous customs to tourists or record companies in Andhra Pradesh India that produce Carnatic music to expand? None. Therefore, the inclusion of every economic sector around the world into the system boundary, regardless of what is studied and what potential changes may be, is misleading and unsubstantiated.

Let us further illustrate the workings of these linear models by a hypothetical fishing net (based on Heijungs (2012)) lying on the ground whose strings are perfectly elastic and knots weightless (Fig. 1a, b). Each knot of the string can be seen as a sector or process and their distance above ground as their output level. Studying the total or life cycle effects of an increase in consumption of a product resembles grabbing hold of a knot, pulling it up vertically, and observing how other knots would respond. As the strings are perfectly elastic, all other knots would be lifted above ground as we pull one, or any, knot up, and by whatever height, 1 mm or 1 m. Those closer to the knot we pull would be lifted higher, reflecting major suppliers being affected significantly, and those farther away may be lifted only slightly, reflecting minor suppliers farther up the supply chain. In addition, if we pull the knot in hand farther up by 1%, 10%, 100%, or 1000%, all other knots would be lifted 1%, 10%, 100%, or 1000% higher above their current position, symbolizing expansion in output in response to the increase in demand.

In reality, however, industries have far more complicated properties and interconnections than assumed above. Most, if not all, industrial processes have non-linear production functions, where increase in output does not necessarily require all inputs to increase proportionally as the Leontief production function assumes (Miller and Blair 2009). For example, farmers can increase crop yields by applying more fertilizers (Hons and Saladino 1995), without applying more irrigation

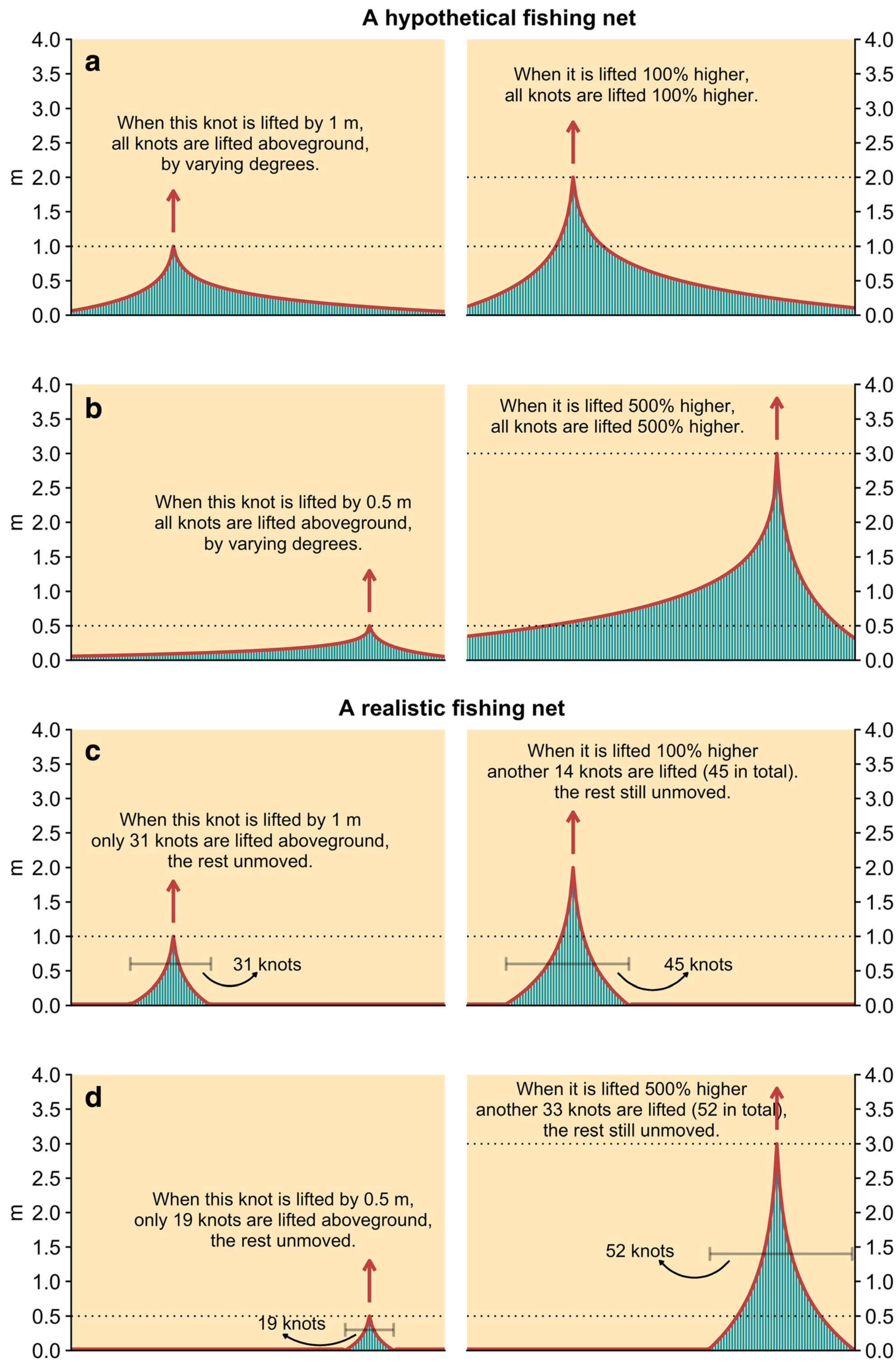

Fig. 1 A two-dimensional projection of fishing nets that illustrate how the conventional linear models, such as process- and IO-based LCA, simulate the economy (**a**, **b**) versus how the economy actually works (**c**, **d**)

water nor pesticides, or by improving management without additional use of fertilizers (Chen et al. 2011). Proportional increases in fertilizers, pesticides, irrigation water, labor, and machinery may be sufficient, but not necessary, conditions for yield increase. Other industries face various constraints, from labor, capital, input materials, and technology, to logistics and climate (Elliott et al. 2014; Golev et al. 2014; Knight et al. 2015). At many places in the economy, there is no full market clearing. One-third of food produced, for example, is not consumed (FAO 2011), and the utilization rate for airplanes (a highly optimized segment of the economy) is around 80% (Mirza 2008). Such examples of idling processes and services are plenty. In addition, many products, and in particular capital goods, are indivisible. As Baumol (1972) wrote, “We cannot install half a blast furnace or half a locomotive.” As important, the “domino” effects in these linear models are assumed to pass through the supply chain only (Eq. 1), but industries can affect each other in other ways beyond the supply chain. One sector may expand at the cost of reducing or displacing another, resulting in a shortage that can trigger further expansion, so on and so forth (Searchinger et al. 2008). That is to say, the chain of effects could spread “horizontally” if supply chain is considered “vertically” (Yang 2017; Rajagopal et al. 2017).

Our real economy can be better illustrated by a real fishing net whose strings have different degrees of elasticity and knots different weights (Fig. 1c, d). How each knot responds to our lift now depends on a range of factors, including which knot to be lifted by hand, at what height, and the weight of each knot and elasticities of the strings to which it is connected. Those close to the knot in hand with elastic strings or light weights may be lifted fairly easily, while those farther away, with inelastic strings or with heavy weights, might not move much or at all. Some knots might even wiggle leftward and rightward, passing the motion to neighboring knots beyond pulling them inward and upward. Lifting the knot in hand further up by 1% might barely move the knots connected to it, let alone the rest of the net. And pulling it up by 100% would likely lift more knots that did not initially move and would further raise the neighboring knots, but likely by varying degrees. Of course, all these responses also depend on how high the knot in hand was initially lifted up.

5 Hybrid LCA with further linear sophistication is a step forward in the wrong direction

A good theory should be based on how firms and household actually behave (Stiglitz 2018). Judging from this criterion, process-based LCA may not be a good theory given all the restrictive linear assumptions and narrow focus on supply chain. Hybrid LCA, through adding the IO model, doubles down on the linearity and narrowness of process-based LCA and thus is a step forward in the wrong direction. It provides little to limited relevance for the questions we address in LCA, e.g., promoting product alternatives. Below we further demonstrate this point through reflecting on advances in corn ethanol research (Yang 2016). In doing so, we also hope to show that the definition of system boundary should be based on cause and effect or how the market responds, beyond the narrow focus on supply chain. And as the fishing net illustrates (Fig. 1), the demarcation of system boundary should be flexible, subject to the product in question, magnitude and direction of change, market conditions, etc., instead of defaulting to a global all-inclusive system boundary under any circumstances.

The question corn ethanol LCA sought to address was whether promoting corn ethanol in the USA would reduce greenhouse gas (GHG) emissions by displacing gasoline. This is a typical question addressed in policy-supporting LCA studies, and conventionally it is approached by estimating the carbon footprint of corn ethanol and gasoline. If the former is lower, then corn ethanol would be worth promoting.

A typical process-based LCA model starts with compiling data on the main life cycle stages of each fuel: feedstock production, refining, transportation, and vehicle operation. For corn production, for example, one collects data on existing cornfields with respect to yield, agrichemical usage, and fuel consumption and then estimates direct emissions (e.g., N_2O emissions from fertilizer application and CO_2 from diesel combustion). The second step is to figure out carbon emissions embodied in all the inputs used in each main life cycle stage, such as pesticides applied during corn growth, catalysts used in petroleum refining, and yeasts used in ethanol refining. This step is typically done using life cycle databases such as GREET and ecoinvent (Wang et al. 2007; Yang et al. 2012). Depending on the database used, the two fuel systems may end up covering dozens to thousands of processes. Early studies using process-based LCA in general found that corn ethanol has a carbon footprint around 20% lower than that of gasoline (Farrell et al. 2006; Hill et al. 2006; Wang et al. 2007), hence concluding that promoting corn ethanol would help mitigate climate change.

According to arguments of hybrid LCA (Lenzen 2001; Suh et al. 2004), the analyses above may not be robust; hence, the ~ 20% difference is questionable. Because the process models used do not have a “complete” system boundary, there may be many processes left out that affect each fuel system differently. For example, Chinese stuffed toy companies may contribute 0.1 g CO_2e to corn ethanol and 0.2 g CO_2e to gasoline when traced through product supply chain. In other words, the two fuel systems could have very different truncation errors, and if a global all-included system boundary were to be covered, their carbon footprints might differ considerably from those estimated by the process models. The percentage difference may be larger or smaller than 20%, and gasoline could even have a lower carbon footprint than corn-based ethanol.

However, the arguments brought by proponents of hybrid LCA miss the real issue with the process-based analyses of corn ethanol. It is not the “incomplete” system boundary that renders its results questionable but the unrealistic assumptions. The conclusion that promoting corn ethanol would reduce GHG emissions is equivalent to saying that the *additional* corn ethanol to be produced would have the same carbon footprint as the *existing* corn ethanol modeled. For it to be true requires all the assumptions to hold such as fixed coefficients, no constraints, and no price effects, as discussed in sections 3 and 4. But most of the assumptions are severely violated in this case, as explained below.

Due to the constraint of land, consequences induced by increased corn production go beyond that associated with its supply chain. The *additional* corn may come from higher yield through more intensive use of fertilizers and pesticides. It may come from direct land use change, e.g., corn expansion into grasslands or forests (Fargione et al. 2008). It may also come from indirect land use change, e.g., corn expansion into other crops (Wallander et al. 2011) triggering land expansion elsewhere (Searchinger et al. 2008). For example, if soybeans were displaced, soybean prices would go up, which could lead farmers around the world to produce more soybeans through clearing of forest and grassland. The *additional* corn may also come from reduced corn supply to livestock sectors, in which case there may not be net increase in corn production. But again, there could be other consequences, such as higher production and consumption of non-meat foods or higher production of other feed than corn. In any of these possible consequences, the carbon footprint of the *additional* corn can be substantially different from—and likely higher than—that of *existing* corn estimated by the process-based models. But none of the consequences was captured by these models possibly due to a failure to recognize their inherent limitations (Yang 2016).

In summary, the linear and supply chain based assumptions behind the process models are highly problematic to begin with. As a consequence, the results in the case of corn ethanol are misleading to policy making (Plevin et al. 2014; Yang 2016). And furthering down the road of linearity and supply chain through hybrid LCA, for example, to include Chinese stuffed toy industry or India's mattress industry in the accounting of corn ethanol's carbon footprint, would make the model even more off in reflecting the reality, hence results more irrelevant. Not only are the theoretical arguments for including the stuffed toy and mattress industries in the life cycle of corn ethanol tenuous, but there is also no evidence they have been affected, in retrospective. More importantly, by focusing on these insignificant processes, we could be masked to what truly matters in understanding the more likely and consequential impacts of corn ethanol expansion, namely, land use changes. More is not necessarily better.

6 Towards a flexible and market-based system boundary and a more realistic modeling of the economy

Before closing, we would like to respond to some recent arguments for hybrid LCA. Schaubroeck and Gibon (2017) suggest that "we must take care not to throw away the baby (hybrid LCA) with the bathwater." As we have argued, not only do we suggest rethinking the direction of hybrid LCA, but we challenge the validity of the original process-based LCA or the entire supply chain based linear framework. Gibon and Schaubroeck (2017) also seem to think LCA unveils "unintuitive relationships between products," which would justify the global all-inclusive system boundary (e.g., yoghurt in Netherlands connected to record companies in Andhra Pradesh India that produce Carnatic music). But within the supply chain linear framework, everything is in theory connected with everything (Suh et al. 2004), so there is nothing unintuitive. The real question is, in our opinion, how likely are the relationships? Consider, again, the US corn ethanol example: its impacts on Chinese stuffed animal production traced through the supply chain are implausible and unlikely, whereas its impacts on global land use mediated through the market are plausible and likely (Searchinger et al. 2008).

Our recommendations for future LCA studies are as follows. First, as we have argued using the fishing net example and corn ethanol LCA research, more accurate linear models do not better reflect impacts of changes. We recommend incorporating other models into LCA to compensate for the limitations of the linear assumptions. Advances have been made on several fronts, such as the incorporation of system dynamics, agent-based modeling, partial and general equilibriums models, and econometric models (Davis et al. 2009; Hertel et al. 2010; Stasinopoulos et al. 2012; Zink et al. 2016).

Second, the question of how to select a proper system boundary merits further and intensive investigation. We argue for a flexible and market-based system boundary that depends on an array of factors including research question, scale of potential change, and market responses. Case studies exploring this topic are especially welcome.

Third, we suggest focusing on key industries that are likely to be affected, rather than those which are many tiers up the supply chain and unlikely to be affected. In the example of corn ethanol, corn, soybean, and possibly other crops that may be displaced by corn expansion should be the focus instead of Chinese stuffed toy industries. In studying the key industries, we should go beyond our conventional practices of simply compiling inputs and outputs. We need to gain a better understanding into how input use (e.g., fertilizer and pesticide) responds to change in output (e.g., higher corn output), what constraints they face, how they expand given the constraints, and in turn how they affect other sectors.

We caution that our arguments against pursuing a global all-inclusive system boundary in the linear models do not mean we should stop collecting environmental data for processes that have yet to be well covered (e.g., rare earth and nanoparticles). Collecting data is one thing, deciding what data to be included in our models is another.

References

Chen X-P, Cui Z-L, Vitousek PM, Cassman KG, Matson PA, Bai JS, Meng QF, Hou P, Yue SC, Romheld V, Zhang FS (2011) Integrated soil-crop system management for food security. Proc Natl Acad Sci 108:6399–6404

Davis C, Nikolić I, Dijkema GPJ (2009) Integration of life cycle assessment into agent-based modeling. J Ind Ecol 13:306–325

Dervis K, Dervis K (1982) General equilibrium models for development policy. Cambridge University Press, Cambridge, p 512

Dixon PB, Jorgenson DW (2012) Handbook of computable general equilibrium modeling. Newnes, Oxford

Elliott J, Deryng D, Müller C, Frieler K, Konzmann M, Gerten D, Glotter M, Flörke M, Wada Y, Best N, Eisner S, Fekete BM, Folberth C, Foster I, Gosling SN, Haddeland I, Khabarov N, Ludwig F, Masaki Y, Olin S, Rosenzweig C, Ruane AC, Satoh Y, Schmid E, Stacke T, Tang Q, Wisser D (2014) Constraints and potentials of future irrigation water availability on agricultural production under climate change. Proc Natl Acad Sci 111:3239–3244

FAO (2011) Global food loses and food waste—extent, causes, and prevention. Food and Agriculture Organization of the United Nations, Rome

Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P (2008) Land clearing and the biofuel carbon debt. Science 319:1235–1238

Farrell A, Plevin R, Turner B, Jones AD, O'Hare M, Kammen DM (2006) Ethanol can contribute to energy and environmental goals. Science 311:506–508

Ferng J-J (2009) Applying input–output analysis to scenario analysis of ecological footprints. Ecol Econ 69:345–354

Gibon T, Schaubroeck T (2017) Lifting the fog on characteristics and limitations of hybrid LCA—a reply to "Does hybrid LCA with a complete system boundary yield adequate results for product promotion?" by Yi Yang. Int J Life Cycle Assess 22(3):456–406. https://doi.org/10.1007/s11367-016-1256-9 Int J Life Cycle Assess 22:1005–1008

Golev A, Scott M, Erskine PD, Ali SH, Ballantyne GR (2014) Rare earths supply chains: current status, constraints and opportunities. Resour Policy 41:52–59

Heijungs R (2012) Spatial differentiation, GIS-based regionalization, hyperregionalization and the boundaries of LCA. In: Ioppolo G (ed) Environment and energy. Milano, Italy, pp 165–176

Hertel TW, Golub AA, Jones AD, O'Hare M, Plevin RJ, Kammen DM (2010) Effects of US maize ethanol on global land use and greenhouse gas emissions: estimating market-mediated responses. BioScience 60:223–231

Hill J, Nelson E, Tilman D, Polasky S, Tiffany D (2006) Environmental, economic, and energetic costs and benefits of biodiesel and ethanol biofuels. Proc Natl Acad Sci 103:11206–11210

Hons FM, Saladino VA (1995) Yield contribution of nitrogen fertilizer, herbicide, and insecticide in a corn-soybean rotation. Commun Soil Sci Plant Anal 26:3083–3097

Isard W (1951) Interregional and regional input-output analysis: a model of a space-economy. Rev Econ Stat 33:318–328

ISO (2006) ISO 14040: environmental management-life cycle assessment-principles and framework. International Organization for Standardization, Geneva

Knight L, Pfeiffer A, Scott J (2015) Supply market uncertainty: exploring consequences and responses within sustainability transitions. J Purch Supply Manag 21:167–177

Lenzen M (2001) Errors in conventional and input output-based life-cycle inventories. J Ind Ecol 4:127–148

Lundie S, Ciroth A, Huppes G (2007) Inventory methods in LCA: towards consistency and improvement. Final Rep UNEP-SETAC Life Cycle Initiat Life Cycle Inventory LCI Programme Taskforce 3:

Miller R, Blair P (2009) Input-output analysis: foundations and extensions. Cambridge University Press, Cambridge

Mirza M (2008) Economic impact of airplane turn-times. AERO Mag Q408

Plevin RJ, Delucchi MA, Creutzig F (2014) Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. J Ind Ecol 18:73–83

Pomponi F, Lenzen M (2018) Hybrid life cycle assessment (LCA) will likely yield more accurate results than process-based LCA. J Clean Prod 176:210–215

Rajagopal D, Vanderghem C, MacLean HL (2017) Life cycle assessment for economists. Annu Rev Resour Econ 9:361–381

Rose A (1995) Input-output economics and computable general equilibrium models. Struct Change Econ Dyn 6:295–304

Schaubroeck T, Gibon T (2017) Outlining reasons to apply hybrid LCA—a reply to "rethinking system boundary in LCA" by Yi Yang (2017). Int J Life Cycle Assess 22:1012–1013

Searchinger T, Heimlich R, Houghton R et al (2008) Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319:1238–1240

Stasinopoulos P, Compston P, Newell B, Jones HM (2012) A system dynamics approach in LCA to account for temporal effects—a consequential energy LCI of car body-in-whites. Int J Life Cycle Assess 17:199–207

Stiglitz J (2018) Where modern macroeconomics went wrong. Oxf Rev Econ Policy 34:70–106

Suh S, Lenzen M, Treloar G et al (2004) System boundary selection in life-cycle inventories using hybrid approaches. Env Sci Technol 38:657–664

Ten Raa T (2006) The economics of input-output analysis. Cambridge University Press, London

Thirlwall AP (1983) Input-output analysis. In: Growth and development with special reference to developing economies. Palgrave, London, pp 231–248

Tilman D, Clark M (2014) Global diets link environmental sustainability and human health. Nature 515:518–522

Wallander S, Claassen R, Nickerson C (2011) The ethanol decade: an expansion of US corn production, 2000–09. US Department of Agriculture, Economic Research Service, Washington DC

Wang M, Wu M, Huo H (2007) Life-cycle energy and greenhouse gas emission impacts of different corn ethanol plant types. Environ Res Lett 2:024001–024013

Weidema PB (2003) Market information in life cycle assessment. Danish Environmental Protection Agency, Copenhagen

West GR (1995) Comparison of input–output, input–output+ econometric and computable general equilibrium impact models at the regional level. Econ Syst Res 7:209–227

Yang Y (2016) Two sides of the same coin: consequential life cycle assessment based on the attributional framework. J Clean Prod 127:274–281

Yang Y (2017) Does hybrid LCA with a complete system boundary yield adequate results for product promotion? Int J Life Cycle Assess 22:456–460

Yang Y, Heijungs R (2018) On the use of different models for consequential life cycle assessment. Int J Life Cycle Assess 23:751–758

Yang Y, Bae J, Kim J, Suh S (2012) Replacing gasoline with corn ethanol results in significant environmental problem-shifting. Environ Sci Technol 46:3671–3678

Yang Y, Heijungs R, Brandão M (2017) Hybrid life cycle assessment (LCA) does not necessarily yield more accurate results than process-based LCA. J Clean Prod 150:237–242

Zink T, Geyer R, Startz R (2016) A market-based framework for quantifying displaced production from recycling or reuse. J Ind Ecol 20:719–729